Modeling and Analyzing the Propagation from Environmental through Sonar Performance Prediction

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LONG-TERM GOALS

Central to the long term goals of this joint project is to understand the physics of the propagation of uncertainty through the interfaces between oceanography, acoustics, array processing and performance prediction. We will develop an efficient overall simulation platform that combines all of the components of the baseline (mean) and uncertainty problem: Oceanography through 4-D acoustic field prediction. The development of a methodology to distill the complexity and uncertainty of the ocean acoustic environment and the system level sensitivities to relevant situational awareness for the operator is an important goal of this research.

OBJECTIVES

The objective of this research program is to both develop a methodology to predict uncertainty in the whole performance prediction process and to understand the uncertainty physics of the individual components of the process. The latter provides the potential to develop methods to reduce uncertainty. We intend to follow a two pronged approach: (1) total model development for Monte Carlo simulation and (2) studying the physics of the interfaces between oceanography, acoustics, array processing and performance prediction.

APPROACH

This project is a joint effort between the parties listed above. We have a two pronged approach: (1) total model development for Monte Carlo simulation and (2) studying the physics of the interfaces between oceanography, acoustics, array processing and performance prediction.

(1) [Cornuelle, Kuperman, Hodgkiss, Thode, Porter/Hursky, Cox/Heaney] Our primary approach to the total uncertainty simulation model development will depend on the usual Monte Carlo runs to convert

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14. ABSTRACT
Central to the long term goals of this joint project is to understand the physics of the propagation of uncertainty through the interfaces between oceanography, acoustics, array processing and performance prediction. We will develop an efficient overall simulation platform that combines all of the components of the baseline (mean) and uncertainty problem: Oceanography through 4-D acoustic field prediction. The development of a methodology to distill the complexity and uncertainty of the ocean acoustic environment and the system level sensitivities to relevant situational awareness for the operator is an important goal of this research.

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an ensemble of oceanographic states to an ensemble of system output showing the range of possible values. This method has the advantage of retaining validity in the presence of strong nonlinearity, as well as being computationally simple.

The ocean ensemble will be coupled to a wide area acoustic propagation model and an accurate array processing model for the purpose of performing area wide performance prediction with an uncertainty measure. Particular care will be given to the mode of representing this information to the operator. We also intend to explore linearized methods for determining system response ranges, based on an analogy to the tangent linear model and adjoint model techniques in use in Physical Oceanography. Applying these concepts the acoustic codes may provide a computationally efficient way to compute sensitivities and transform ocean state uncertainty covariances to system performance uncertainty covariances. Further, it is hypothesized that this approach may be more applicable to the total problem rather than stopping at the acoustics output because, to a certain extent, performance prediction is somewhat of a "smoothing" process, possibly enabling the required linearization mentioned above. We consider this part to be a high-risk high-payoff idea, in that to our knowledge, the oceanographic data assimilation adjoint approach has never been applied to acoustic models, much less to the whole performance prediction process.

Uncertainty occurs in the geometry (source/receiver locations, bottom depth), the bottom properties, the surface properties (sea state and resulting bubble clouds and surface roughness), and the ocean volume (internal waves/tides, meso-scale features such as eddies, and fronts). The uncertainty of many of these is easy to characterize. For instance errors in receiver locations are a function of the performance of depth-heading sensors on the arrays; their performance may vary over time on a given array but by and large there are no interesting scientific issues about their accuracy. The most interesting and perhaps important of the above listed uncertainties, is that due to the oceanography and how it subsequently regulates acoustic bottom interaction with uncertain geophysical parameters.

The ROMS primitive equation model will be used to simulate the small-scale features in an area of interest. Separately, a simpler internal wave model will be used to characterize the space-time structure of the internal wave field that will be excited using a uniform energy density of internal waves. In an operational scenario, we envision that one or the other of these models will be used to predict the statistics of the oceanographic variation. The primitive equation model is not viewed as a tool that would predict a deterministic environment but rather as something that might provide a more accurate prediction of the typical variation. The 1-D internal wave model is obviously simpler and computationally more practical, but may be less accurate. One objective will be to compare the relative merits of the two approaches.

The existing acoustic models produce a realization of the pressure field for a single deterministic environment (which is obviously distinct from a mean field). To capture the uncertainty the acoustic models will need to be enhanced to rapidly produce an ensemble of pressure fields or statistics of the ensemble. The algorithmic approach we will develop in this program is different in each of the 4 standard model types. However, the common starting point for all of these is the "environmental endpoints," i.e., the limits (or, more precisely, variances) characterizing the uncertain environment. Despite the variety of sources of uncertainty, they can all be treated using the same framework as will be discussed below. To fix ideas, imagine a mean sound-speed profile and a lowest-order EOF characterizing the variation due to the first baroclinic mode. The "environmental endpoints" are the mean with that EOF added and subtracted based on the excursion seen in the oceanographic data. If the internal wave model is found to be adequate, it will be integrated with the acoustic model so that an

input SSP is used first to drive the internal wave model, and then passed directly to the acoustics model along with the environmental endpoints calculated by the internal wave model.

We also expect to use the tools that we have developed to study the viability of: (a) assimilation of acoustic data from ships of opportunity; this might involve data fusion with remote sensing or the use of battlegroup location via netcentric operations and (b) optimizing ASW area coverage in a way that reduces uncertainty by accumulating and assimilating data during operations.

(2) [Krolik] The results from the total simulation approach presented above will be difficult to interpret in terms of the individual physics components of our program. Hence, there will be a need to study the interfaces between the components. We will develop computationally efficient mappings of random oceanographic state variables into representations of the acoustic pressure field received at a sensor array. The goal is to accurately capture the spatial wavefront uncertainty of submerged and surface acoustic sources in order to improve *in situ* passive sonar performance prediction. The emphasis, therefore, will be to develop computationally fast methods for mapping high-dimensional random oceanographic state variables to functions of the acoustic wavefront used to form target detection statistics. Both the classical complex multivariate Gaussian wavefront model and the proposed non-Gaussian pseudo-multipath expansion (PME) model will be evaluated for different passive sonar scenarios in uncertain oceanographic environments. To benchmark these fast solutions, sonar performance predictions for limited complexity cases will be compared to those obtained by Loren Nolte (see below) using Monte-Carlo estimation techniques. Oceanographic uncertainty will be characterized by the mean and covariance of mesoscale state variables generated by Cornuelle's extensions to the Regional Ocean Modeling System (ROMS) and statistical characterizations of internal wave variability developed by Heaney Computational models developed by Porter and Kuperman will be used to generate realizations of the acoustic field in highly inhomogeneous range and azimuthally dependent littoral environments.

[Nolte] The acoustics/signal processing interface involves understanding the optimal detection, classification, and localization framework that incorporates uncertainties in ocean environmental parameters directly into the computation of improved sonar performance prediction. Beyond merely predicting performance degradation due to environmental uncertainties, we also seek to identify those physical parameters whose uncertainties affect detection performance prediction the most. By formulating hypothesis testing problems which properly incorporate the effects of uncertain parameters, we will provide performance measures, such as Receiver Operating Curves (ROC's) and localization ROC's, which more accurately include the uncertainties of the realistic detection problem faced by an operator in a complex littoral environment, than does the classic sonar equation. The input to this formalism, is mesoscale and internal wave simulations from above as well as the acoustic propagation simulations as passed through the Krolik's wavefront distortion representation. This "data" will be incorporated into the formulation of uncertainties for our hypothesis testing approach to sonar performance prediction. This will utilize and complement the statistical characterization of the uncertainty of physical parameters, per se, as determined by the ocean modelers. In addition to IMAT like outputs, various presentations to the operator will be considered, such as probability of detection contours versus range/depth/bearing, for fixed probability of false alarm, as a function of ocean environmental uncertainties.

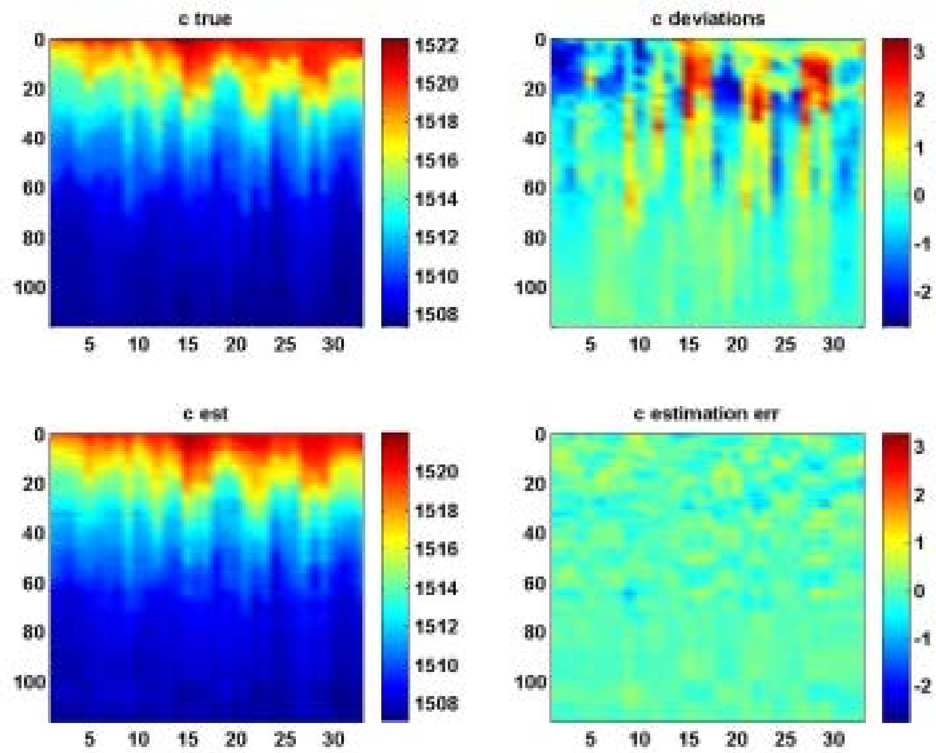

Figure 1. Results of inversions for internal tides using our adjoint model.

Throughout the program, we will have as underlying theme and goals, the construction of a methodology for capturing uncertainty in performance prediction from the overall system perspective. The focus of this work will be distilling the complexity and uncertainty of the ocean acoustic environment and the system level sensitivities to relevant situational awareness for the operator. [Cox will lead/coordinate this aspect of the program].

WORK COMPLETED

We have configured and run the ROMS model for the Southern California Bight (SCB) region, embedding higher resolution grids within thedomain of the lower resolution grid which has been run to simulate and assimilate the CalCOFI data. We have completed a first attempt of coming the PE Acoustic model with the adjoint methodology. An adjoint model enables calculations in the space of observations, usually much smaller than the space of medium properties, especially in range-dependent environments. This reduces the computational burden of inversion processes and sensitivity/error analyses, and enables larger problems to be addressed. Along with numerical studies, we have studied the adjoint/ocean/acoustic approach analytically. We have developed a ray-based interpolation technique for computing TL that can be used with Monte-Carlo methods since run times are reduced factors of 100–1000. Ray based propagation models are common in the SONAR community but usually a new ray trace is required each time environmental conditions change. We have developed a set of basic acoustic Observables (BOA) that summarize the relevant acoustic propagation physics. By using the TL slope (or TL level at a set of ranges), the time-spread and the slope of striations observed in passing surface ship data in shallow water, as our observables, we have a mechanism for quantifying and communicating the uncertainty in acoustic variables in a manor that is relevant to the operator. We have also applied two complementary approaches to study the impact of ocean environmental

uncertainty on passive sonar performance prediction. The first employs an optimal Bayesian hypothesis testing framework to obtain detection performance prediction algorithms that incorporate the degree of ocean environmental uncertainties, as well as SNR. The second approach, uses the performance of optimal adaptive CFAR detection statistics to bound sonar performance in the presence of both environmental uncertainty and unknown noise field directionality. Both approaches significantly generalize calculations based on the classical sonar equation, which tacitly assumes a deterministic (known) ocean environment and known noise field directionality.

RESULTS

Figure 1 shows the adjoint results of inversions of pressure observations (simulated) for sound speed perturbation in the water column, given a mean profile as a baseline. The upper left plot shows the "true" profiles. The lower left plot shows the estimated profiles. The upper right plot shows the "true" profiles minus the mean profile. The lower left plot, shows the estimation errors. For the Bayesian approach, results include the development of an efficient means of evaluating the statistics of a robust Bayesian detector in an uncertain ocean. This permits the calculation of detection performance ROC's much faster than using Monte Carlo techniques. More importantly, these initial results show that optimum detection performance prediction with ocean environmental uncertainties and diffuse noise background depends primarily on the rank of the received propagated signal correlation matrix, which is a measure of the scale of ocean environmental uncertainties, and the SNR. The optimal Bayesian detection performance predictor has been compared and shown to be much superior, as uncertainties increase, to the predictor based on the mean ocean environmental parameters. For the adaptive CFAR approach, results include the evaluation of a newly modified detection performance figure-of-merit (FOM) which incorporates signal wavefront uncertainty, characterized by signal rank and the number of noise training data snapshots available. Detection performance was evaluated using real noise field directionality measurements from a horizontal towed-array in shallow-water with best-case/worst-case FOM estimates translated to maximum/minimum range-of-the-day predictions.

IMPACT / APPLICATIONS

This expected impact of this project is to provide a methodology to provide a reliability measure to the operator of at-sea performance prediction models.

TRANSITIONS

No transitions took place in FY02.

RELATED PROJECTS

This is one of the programs in the ONR UNCERTAINTY DRI.

PUBLICATIONS

P. Hursky, M. B. Porter, B. D. Cornuelle, W. S. Hodgkiss, amd W. A. Kuperman, "Adjoint-Assisted Inversions for Shallow Water Environmental Parameters," in *Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance* Eds: Nicholas Pace and Finn Jensen, Boston: Kluwer Acadmic Publishers, 2002. [ISBN 0-4020-0816-3].